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DRAFT

LAUNCHING OF MICRO-SATELLITES USING GROUND-BASED HIGH POWER PULSED LASERS

DEPS 6TH Annual Directed Energy Symposium

20-24 October 2003

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Agenda

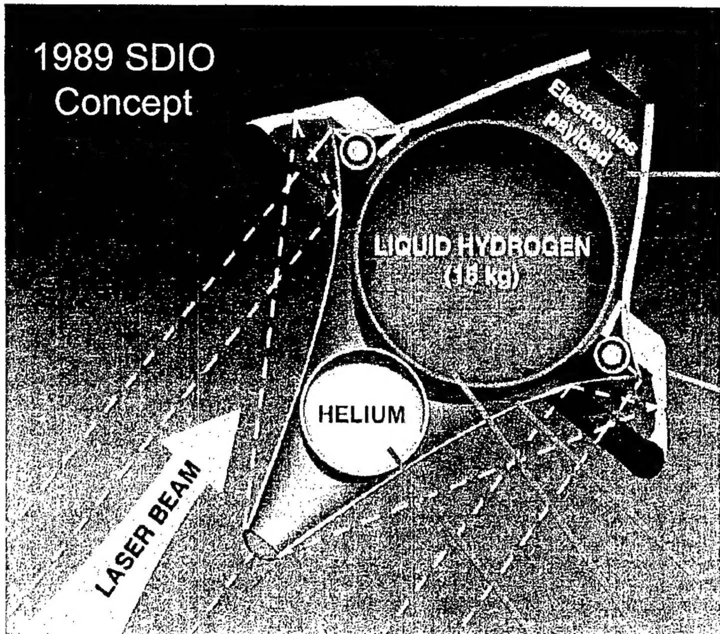
- Laser Propulsion Concept
- Candidate High-Power Lasers
- Pulsed Carbon Dioxide Laser Technology Overview
- Relevant Legacy Programs
- Candidate Concepts/Architectures
- Propagation Enhancement Concepts
- Program Plan/Schedule
- Conclusions

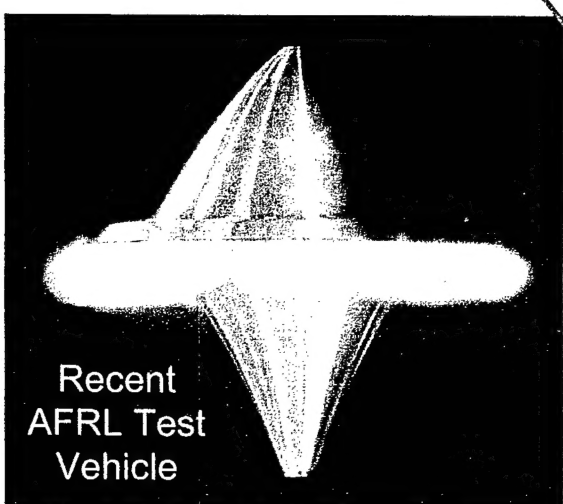
Why Laser Propulsion?

- **Benefits**
  - ➢ Avoids carrying heavy propulsion system components through the atmosphere and into space; the laser is not on board
  - ➢ Higher performance potential than chemical rockets
  - ➢ Higher thrust than electric propulsion concepts
  - ➢ None of the polluting or radioactive exhaust associated with chemical or nuclear rockets
  - ➢ Can be accomplished by extensions and integrations of existing rocket propulsion technologies; no physics breakthroughs required
  - ➢ Repeatedly shown to be economically viable; AF, NASA, and DARPA have all done independent studies
- **Draw Backs**
  - ➢ Requires expensive, high power laser which is typically not mobile
  - ➢ Lacks complete demonstration after 33 years from conception

The benefits outweigh the negative aspects!

The Lightcraft Concept





- A Lightcraft is a small spacecraft; diameter is about 1 m, weight is about 2 kg (1 kg payload)

Forebody

- ➢ Aerodynamically contoured surface
- ➢ Analogous to rocket payload bay; opens in space to release payload and expose solar cells

Shroud

- ➢ Centrally located "belt"
- ➢ Analogous to rocket combustion chamber; ejected plasma provides thrust

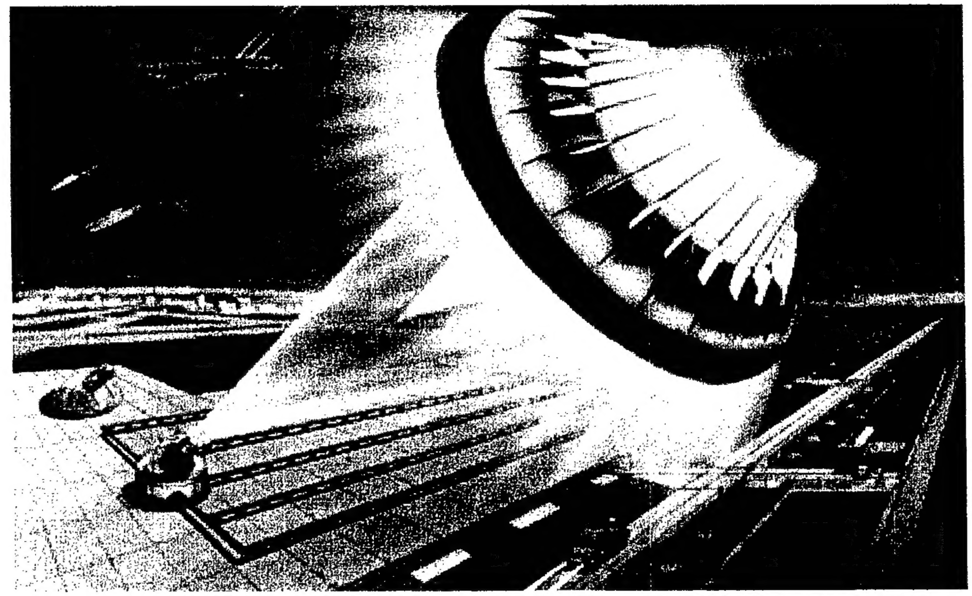
Afterbody

- ➢ Analogous to rocket nozzle; parabolic mirror and plug nozzle (resolution: 7 to 15 cm)

Large tank holds liquid propellant (N_2, NH_3, or H_2) for use in space

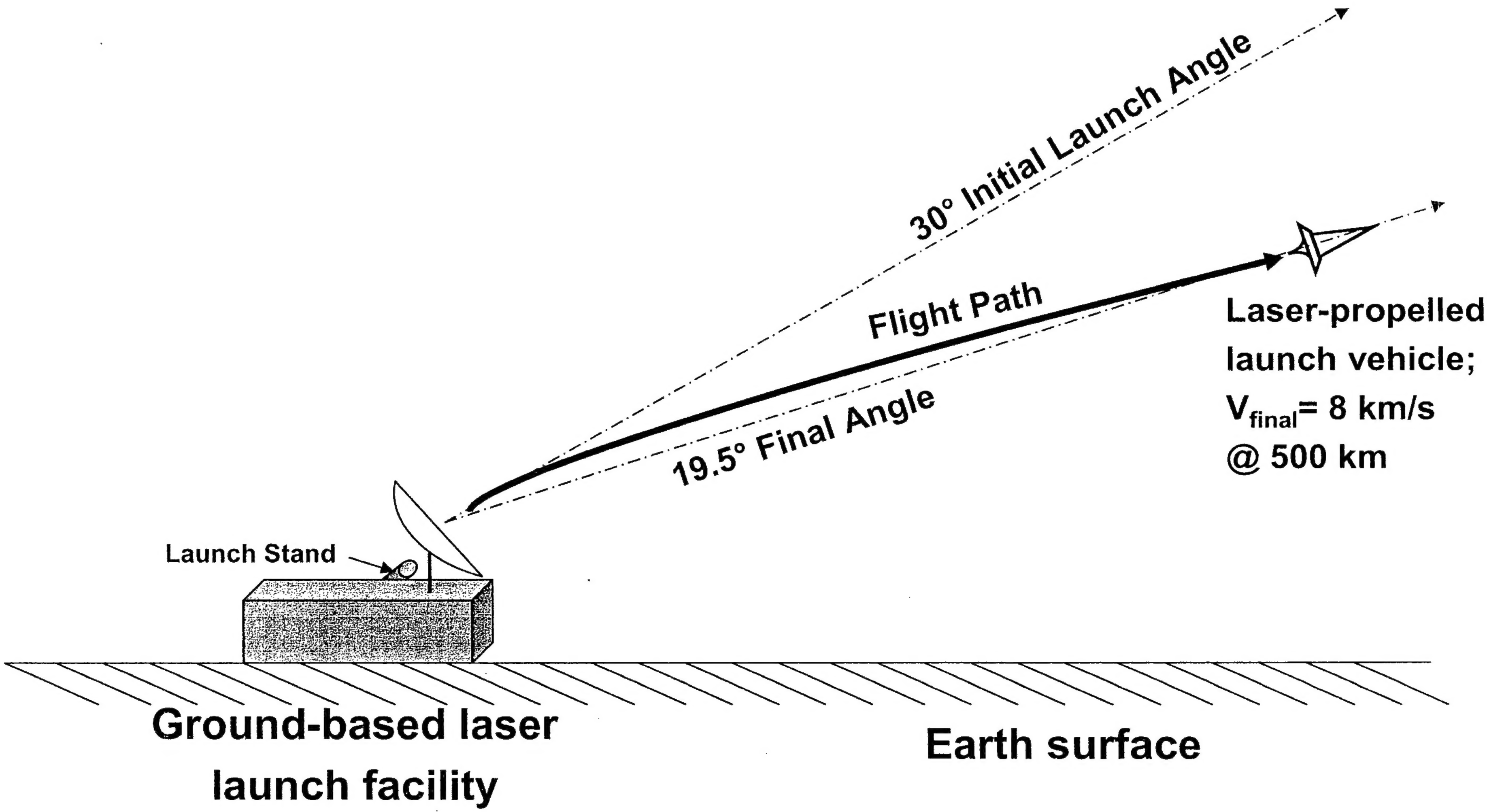
Small tank holds gas (He) for attitude control

Low Cost Access To Space:
The Primary Lightcraft Application

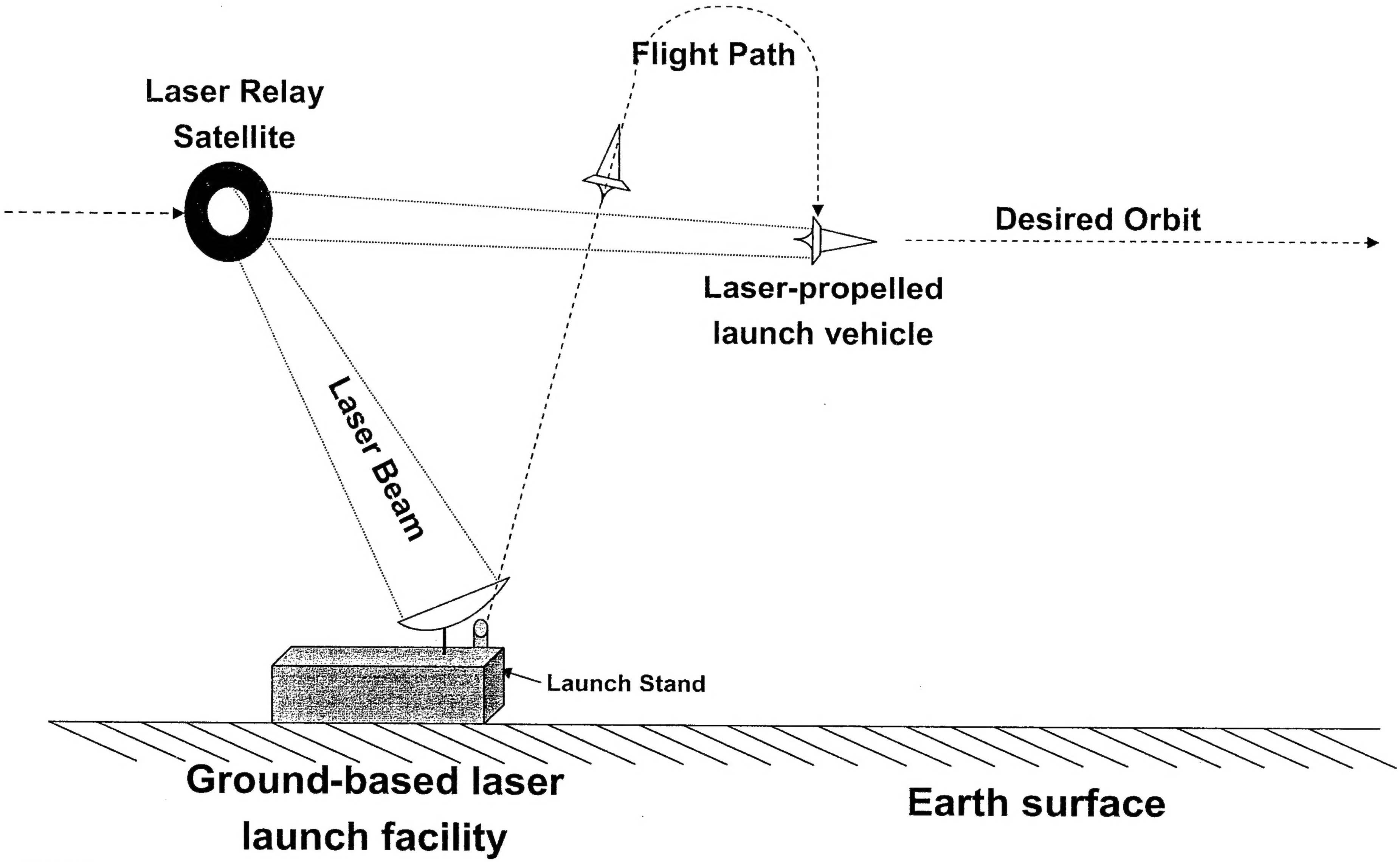


- Laser-propelled beam rider
  - Rides ground-based laser beam into space
  - Single stage to orbit
  - Very high performance
  - Airbreathing in atmosphere, uses propellants in space
  - Launch on demand to anywhere in low Earth orbit
- Simple, reliable, safe, environmentally clean
- High launch rate – anywhere, anytime with electric laser
- Less than \$500 of electrical power (~\$150/lb) needed to reach low Earth orbit
- Vehicle production cost estimated at \$3,000 per vehicle (1 kg payload)
- Interest in this concept expressed by AF, NASA, DARPA, NRO

Ground-Based Laser Launch:
Launch From A Single Site ("89" SDIO Study)



Ground-Based Laser Launch:
With Use Of Space Assets ("89" SDIO Study)



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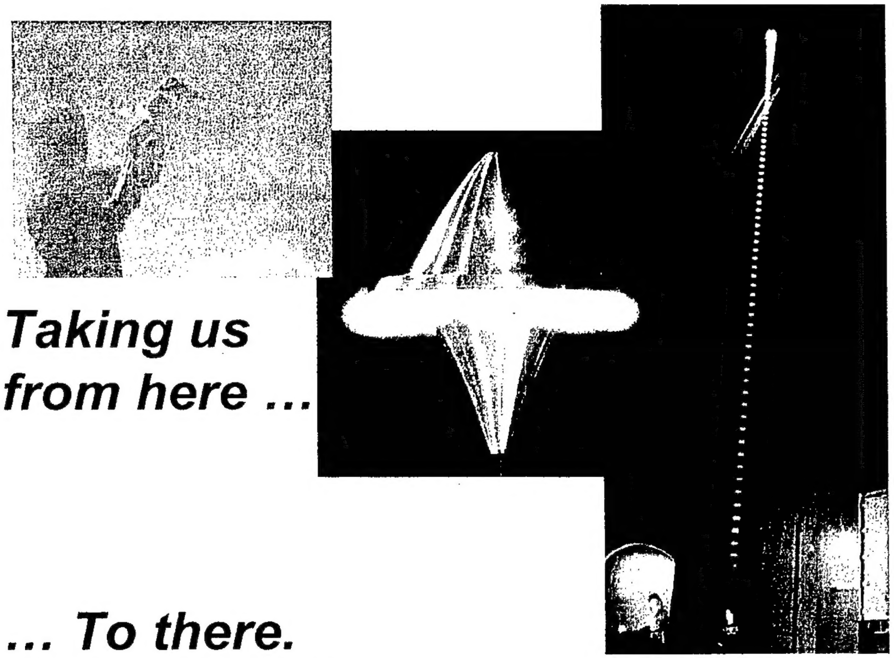
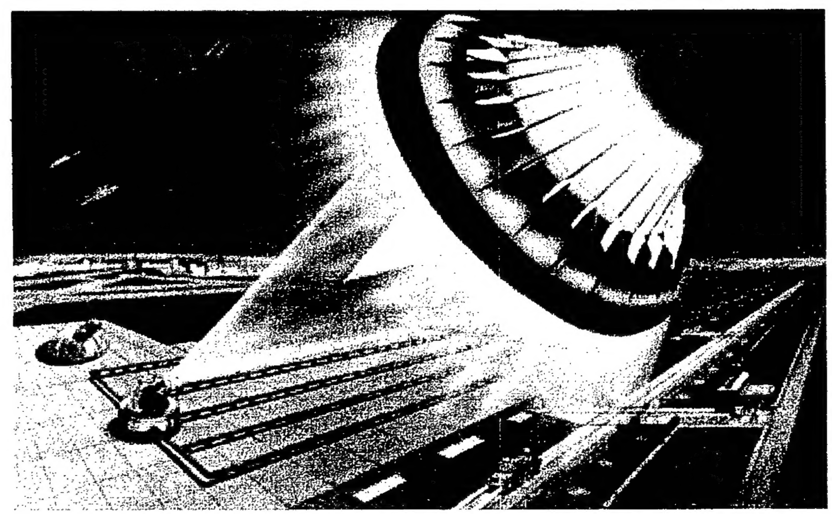
Program Summary

- Feasibility demonstrated through a series of historic flights and experiments at White Sands
- Composite materials and a 100-kW laser will enable vertical flights to the edge of space within a few years
- No technology breakthroughs are needed, although construction of a MW class laser and large beam director will be required
- Laser propelled vehicles could be useful in a wide range of applications



Taking us from here ...

... To there.



Laser Propulsion technology has the potential to make low-cost access to space a reality in the near future

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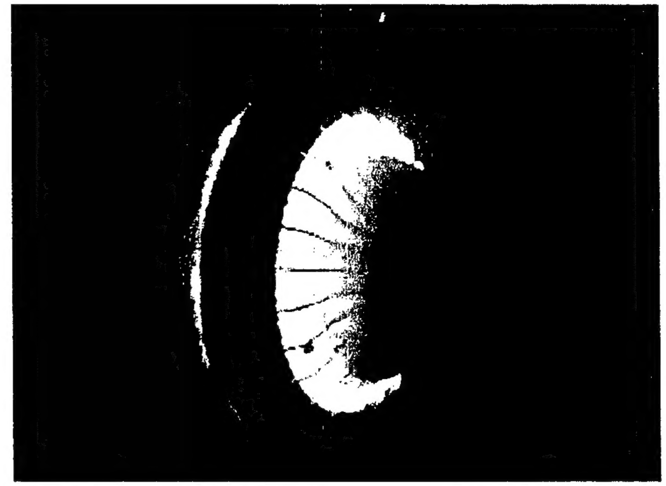
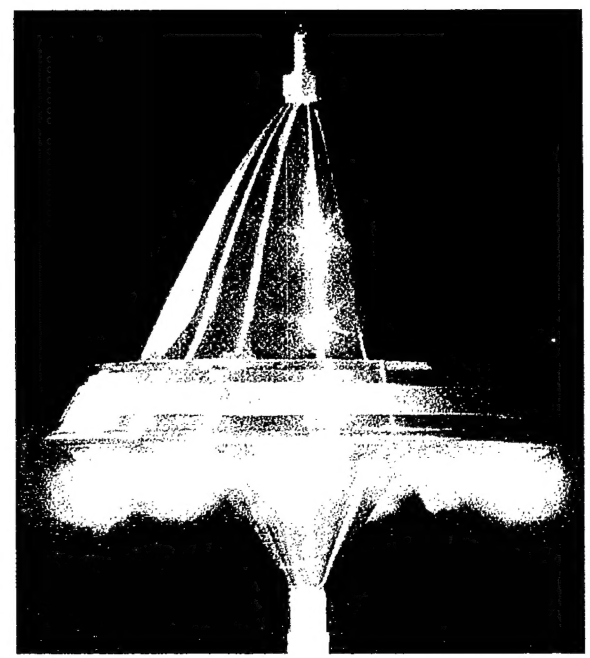
Additional Laser Propulsion Applications

- "Nanosatellites" : 1 to 10 kg – for a wide range of applications
  - Potential use by AF, NASA, BMDO, NRO, communication companies, private industry, individuals
  - Launch on demand to anywhere in low Earth orbit
- A vehicle can be configured as one-meter diameter telescope, making it useful for:
  - High-resolution imaging, surveillance, and mapping
  - Global positioning and tracking
  - Threat detection and tracking
  - Communications and relay
  - Astronomy





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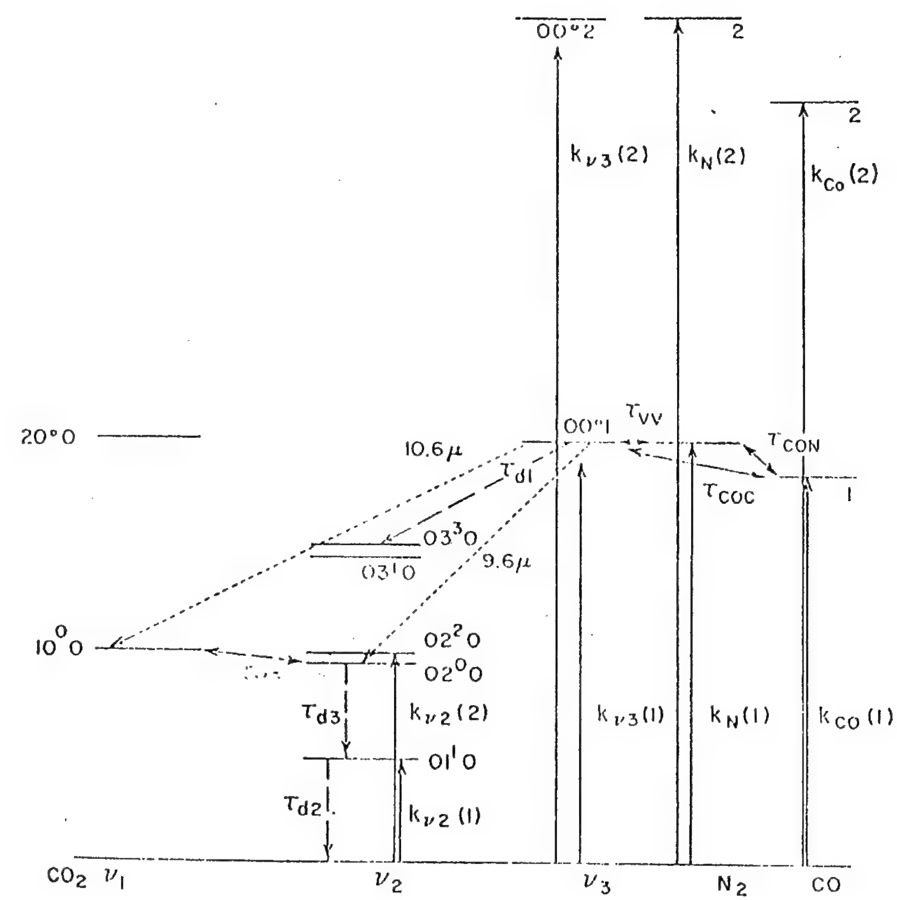
CANDIDATE HIGH-POWER LASERS

LASER	ISSUES
CO2*	LARGE λ, ATM. ABSORPTION
CO*	LARGE λ, ABSORPTION, TOXICITY
HF/DF*	ABSORPTION, CORROSIVE CHEMICALS, PULSE ENERGY (?) RUNNING COST, BEAM QUALITY
OXYGEN IODINE*	CHEMICALS, PULSE ENERGY (?) RUNNING COSTS
NEODYMIUM	COST, AVERAGE POWER, RUN DURATION

*MW-CLASS AVERAGE POWER LEVELS DEMONSTRATED

PULSED CARBON DIOXIDE LASER TECHNOLOGY OVERVIEW

Energy Levels for the Three Vibrational Modes in the CO_2 Molecule with those of N_2 and CO



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Basic Rate Equation and Discharge Categories

$$\dot{n}_e = S + (a - \beta)n_e - \gamma n_e^2 \quad (1)$$

$S =$ E-BEAM SECONDARY ELECTRON GENERATION RATE

$a =$ IONIZATION RATE

$\beta =$ ATTACHMENT RATE

$\gamma =$ RECOMBINATION RATE

- E BEAM SUSTAINED

$$N_E \quad \sqrt{S / \gamma}$$

- S/SUSTAINED LONG-PULSE

$$a = \beta @ (E / N)_G$$

- S/SUSTAINED SHORT-PULSE

$$\gamma N_E >> \beta$$

$$a \quad \gamma N_E$$

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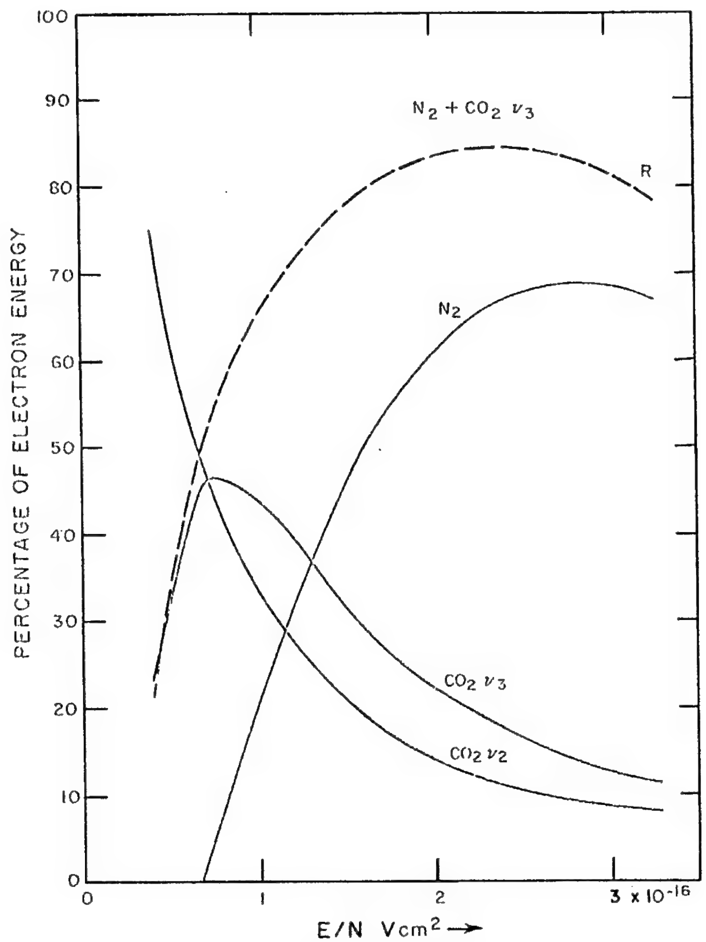
Fraction of Discharged Energy Deposited in Various Modes of a He: N_2: CO_2 3:2:1 Mixture



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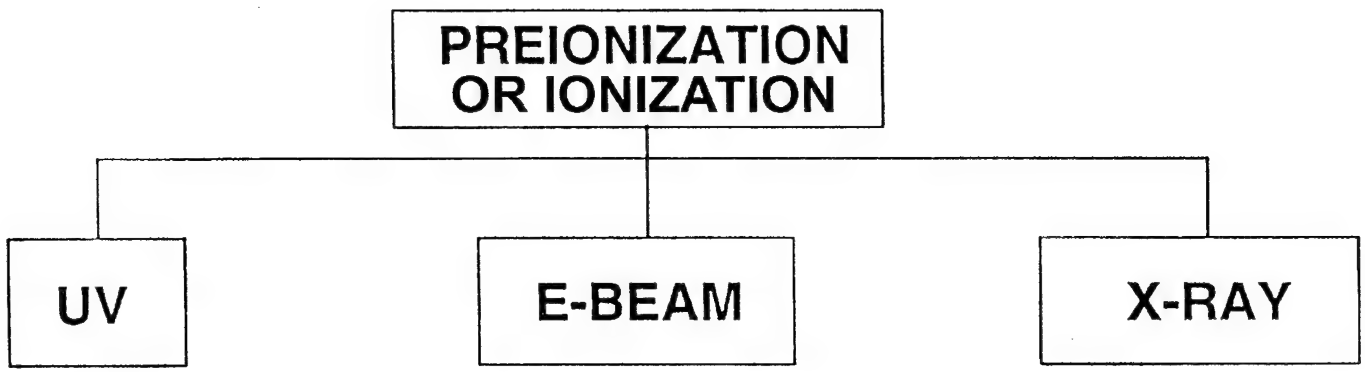
Discharge Preionization or Ionization Options



UV

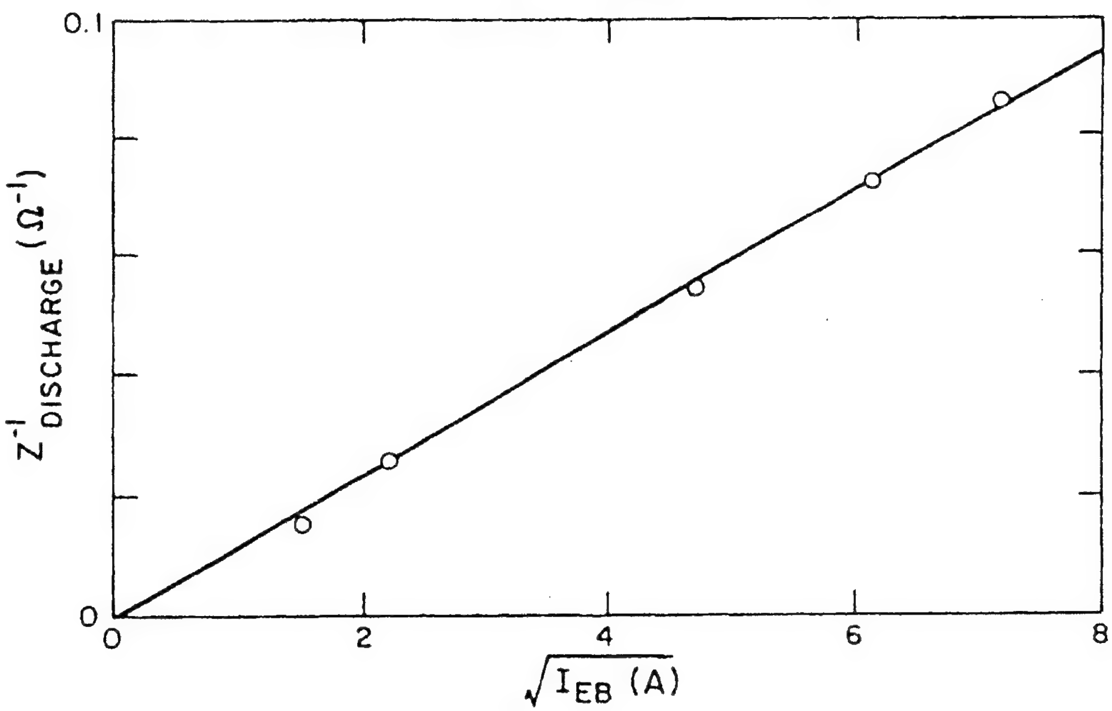
- FLUSH FACTOR
- ENERGY LOADING
- APERTURE SCALING

X-RAY

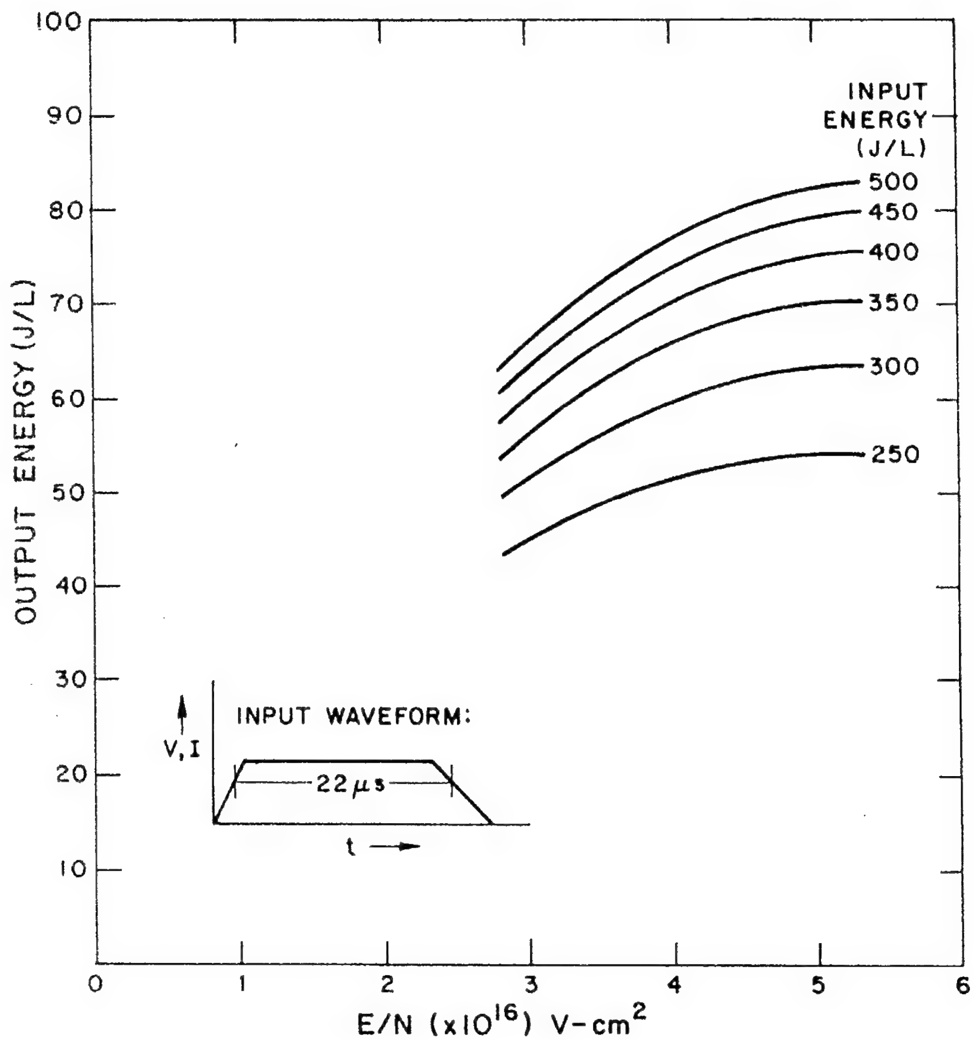
- FLUSH FACTOR
- ENERGY LOADING

Experimental Data Verifying Conductivity Dependence of E-beam Stabilized Discharge

$$n_{eo} = \sqrt{S/\gamma} \qquad (2)$$



Specific Output Energy (Room Temp-gas)



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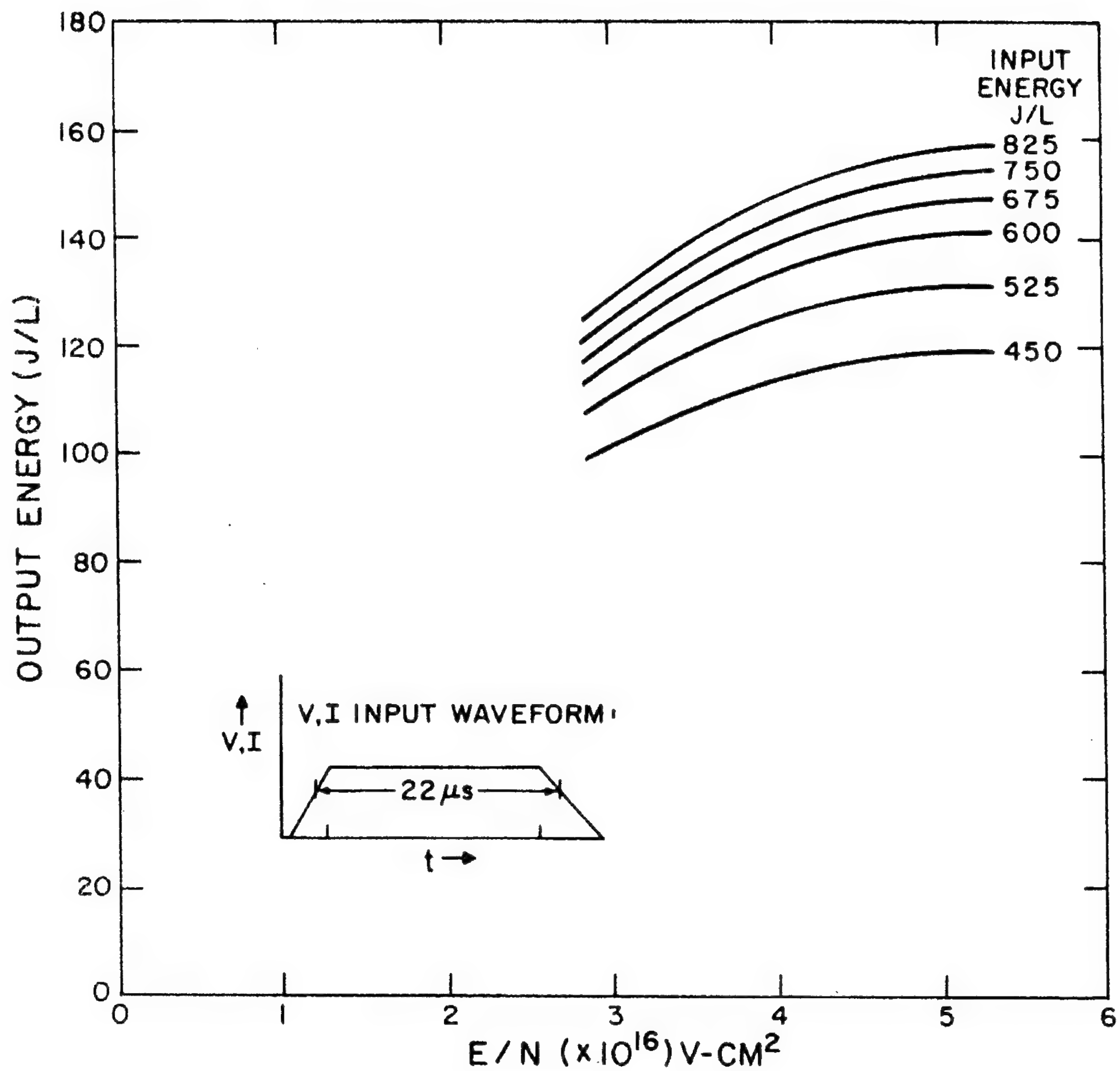
Specific Output Energy (Cold-gas - 220°K)



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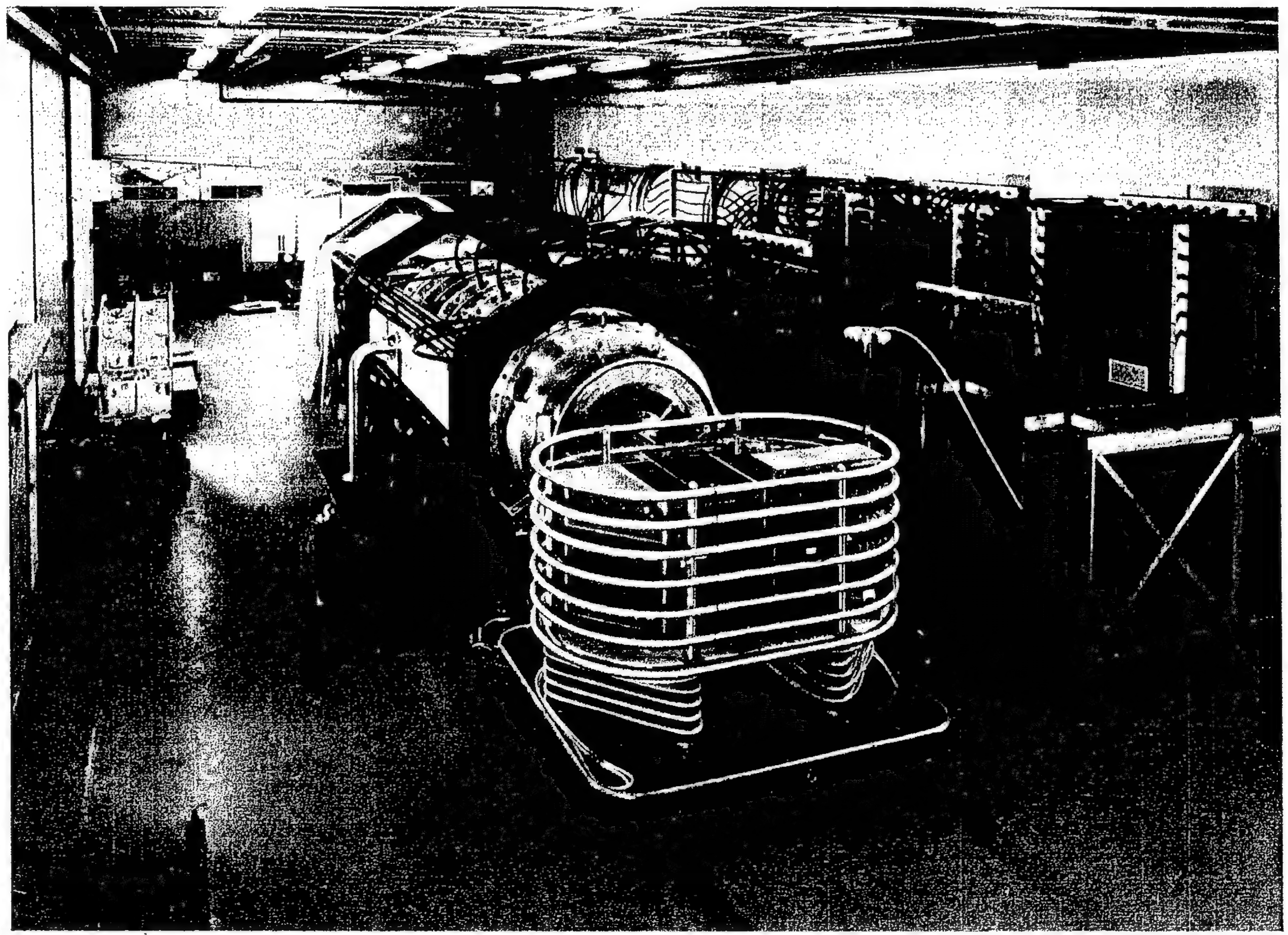
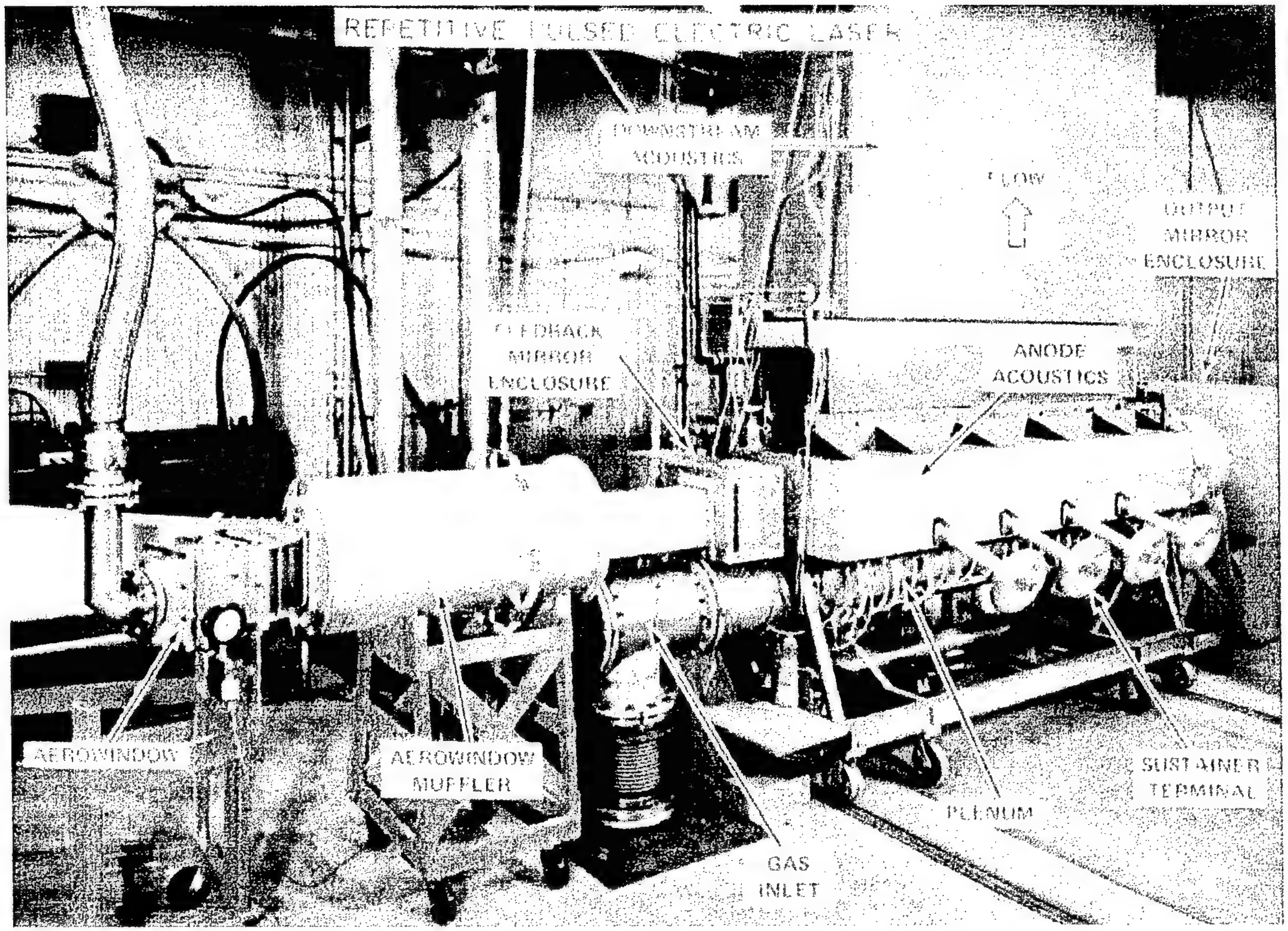
RELEVANT LEGACY PROGRAMS

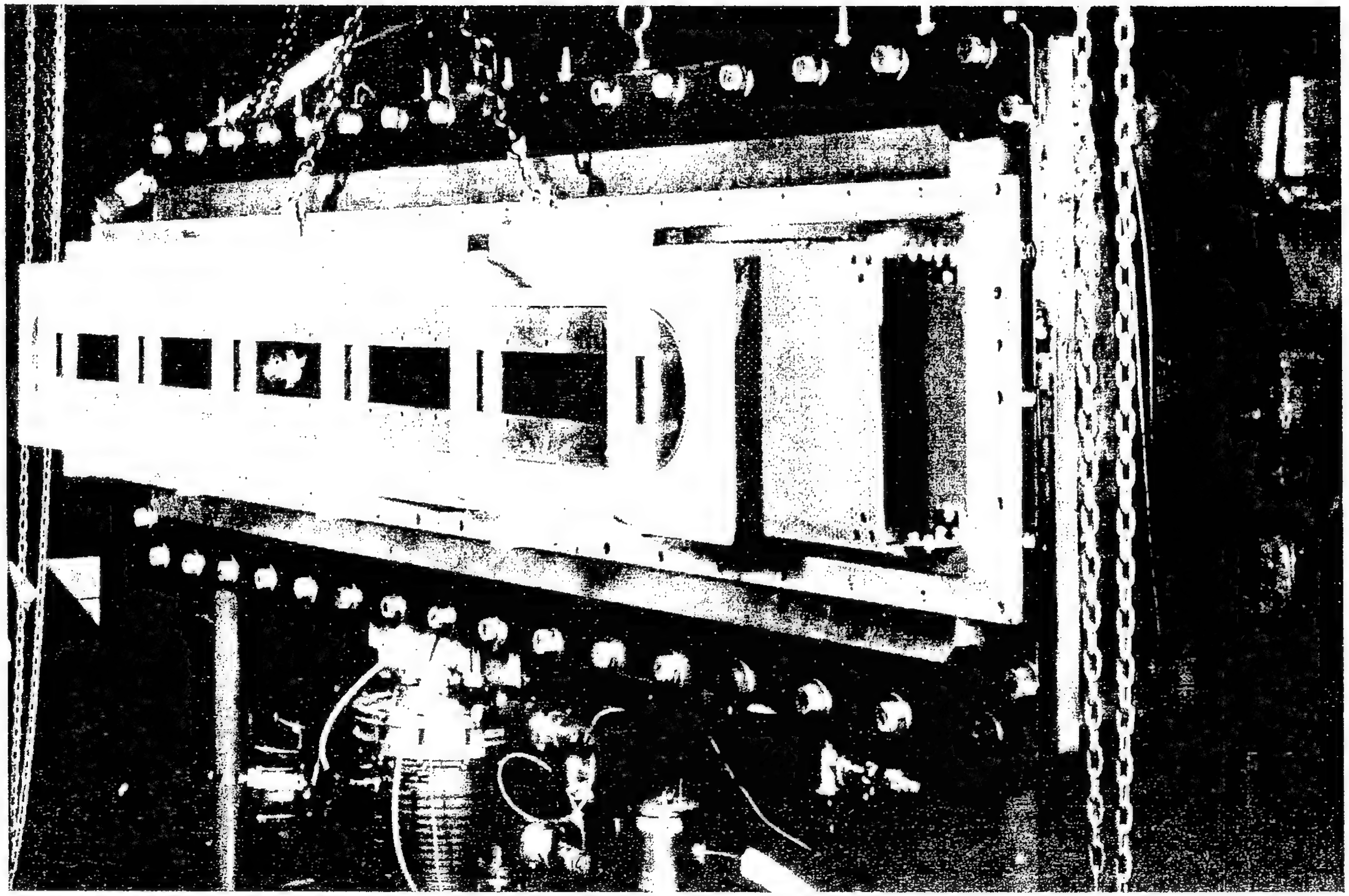
Thumper Laser



ABEL Breadboard Laser



25 X 200 CM ABEL E-Gun



Candidate Concepts/Architectures

- *100 kW CO_2 Pulsed Laser*

- *Multi-Megawatt Class Pulsed CO_2 Laser*

Closed-Cycle 100 kW Transmitter

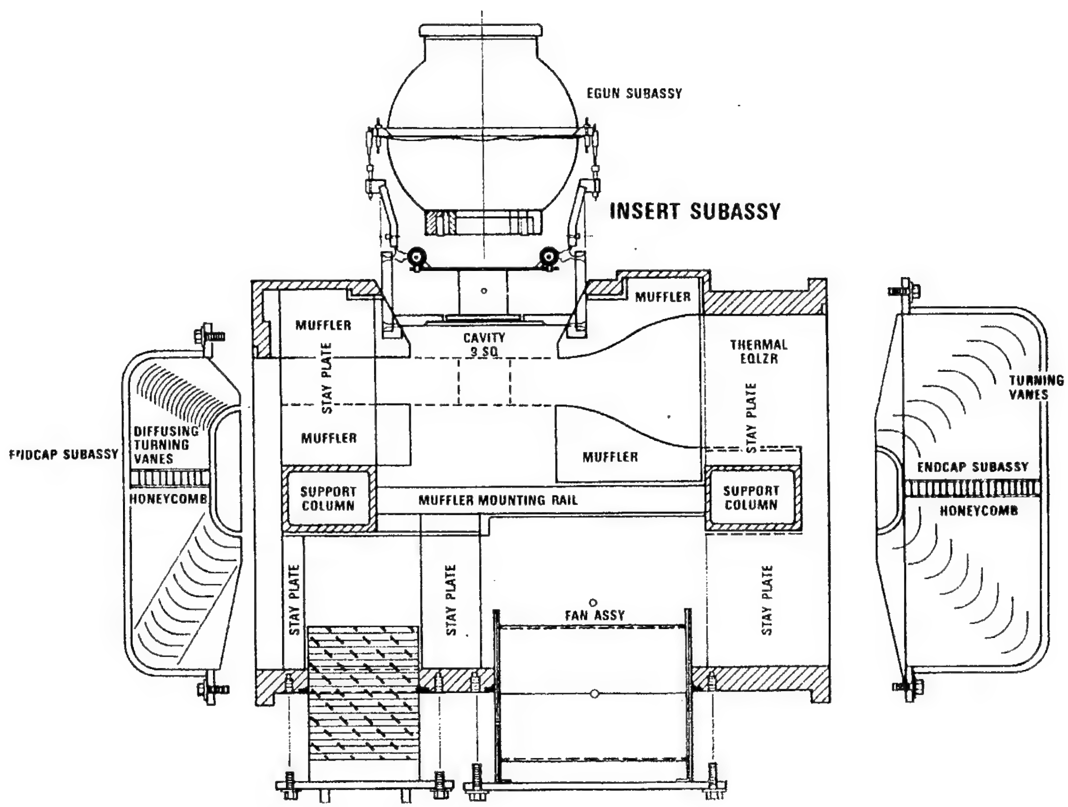
ADVANTAGES

- DESIGN BASED ON PREVIOUSLY DEVELOPED POWER AMPLIFIER (GOVERNMENT FUNDED LICD CONTRACT)SYSTEM
- AVOIDS DIFFICULTIES OF SIGNIFICANT SCALING + RETROFIT
- RUNS ANY GAS MIXTURE/ISOTOPES
- RELATIVELY SMALL FOOTPRINT
- COULD USE SOME EXISTING HARDWARE (e.g., E-GUN, BUSHINGS, ETC)

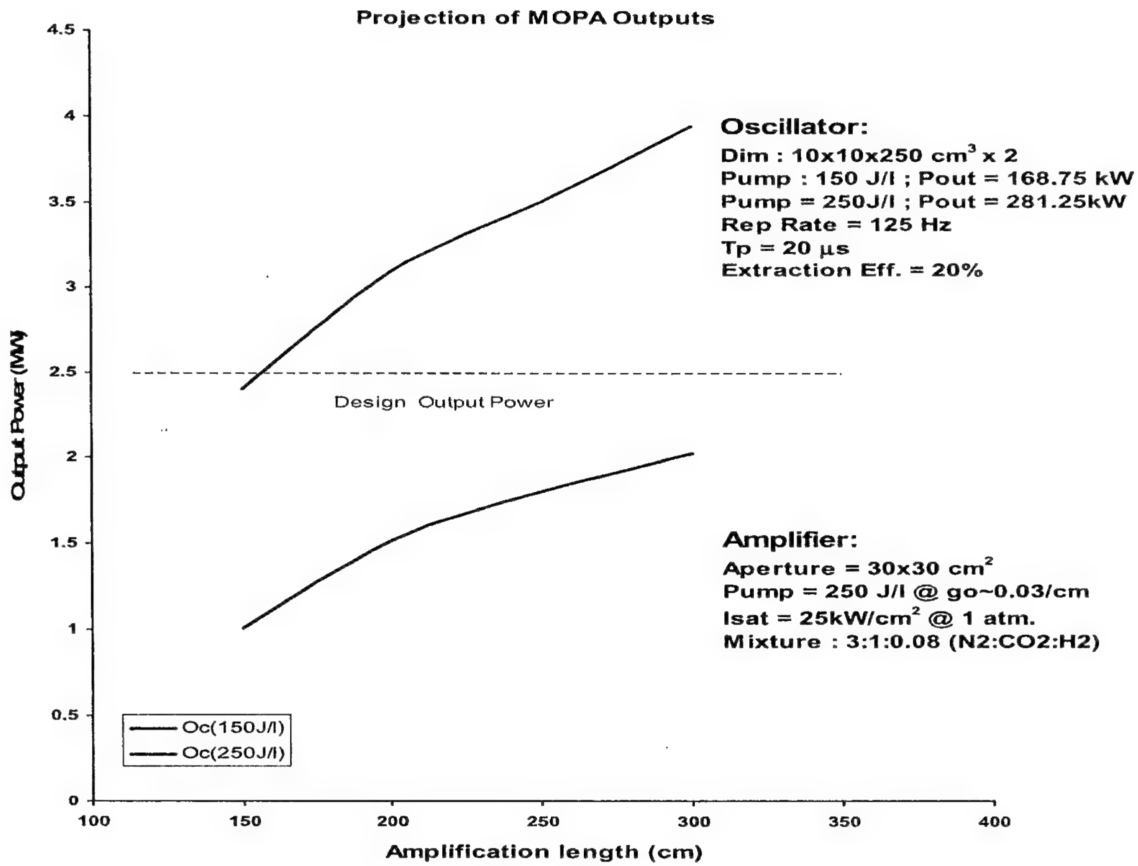
DISADVANTAGES

- REPRESENTS STATE-OF-THE-ART WHICH ENTAILS SOME RISKS
  - DVT's will be required to support PDR
- IN-LINE CATALYSIS WILL BE REQUIRED FOR LONG-DURATION ISOTOPE RUNS
- LONGER DEVELOPMENT TIME COMPARED WITH OTHER OPTIONS

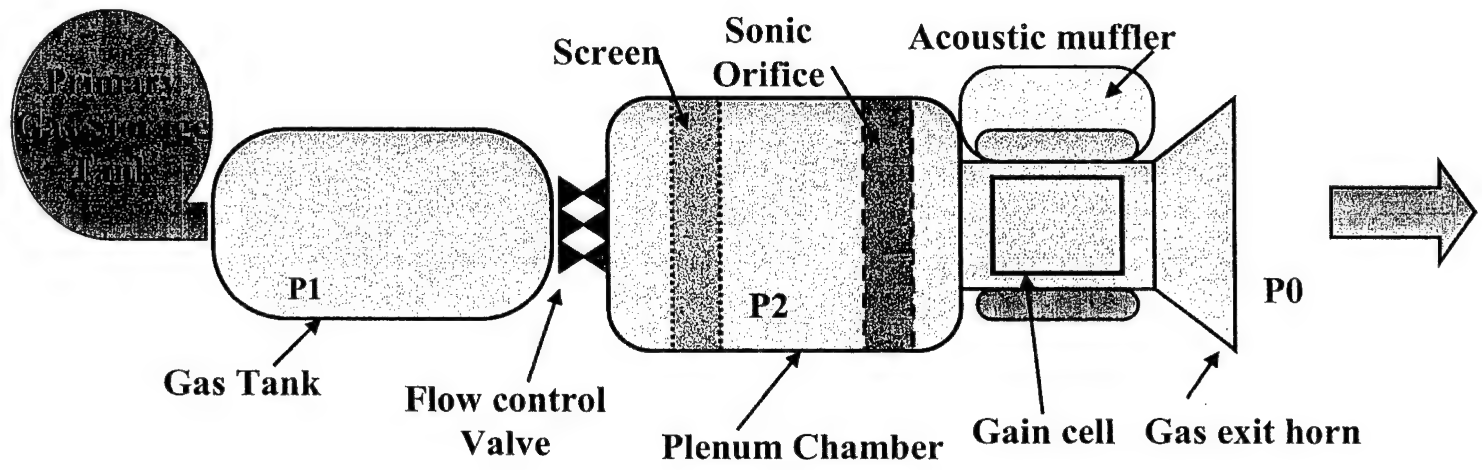
Representative Schematic of Flow Loop Components



Projected MOPA Outputs



Schematics of Flow system



Gas Pressure :
P1 = 150 Atm
P2 = 2 - 2.5 Atm
P0 = 1 Atm (ambient)
Flow speed : 50 m/s

Gas Physical Parameters:
Mixture : N2:CO2:H2 (3:1:0.08)
a = 271 m/s (acoustics)
M = 0.18 (Mach No)
m=31.5 (Effective Molecular Weight)
Density = 1.3 kg/m^3

Laser Operation Requirements

Flow System: ***Blow down***

- Gain section

Cross Section : A=0.3 x 3.0 = $0.9\ m^2$

Volume : V = 0.3 x 0.3 x 3.0 = $0.27\ m^3$

Flow speed : u=*50 m/s* (@ 125 Hz & flash factor=1.3)

Dynamic pressure : ΔP=*2000 Pa* (0.02 Atm)

Mass flow rate : q=*60 kg/s* / module (45m^3/s std)

Run time : t = 300 sec

Total : Q=*240 kg/s (72m tons)*

- Plenum chamber:

Volume : V2=0.5 x 3.0 x 1.5=$2.25m^3$

Static pressure : P2 = 2.02 x 10^5 **Pa (2 atm)**

Sonic orifice plate : perforation = *17.5 %*

Flow screen : loss > 0.2 - 0.3

Skin friction : loss ~ 0.08

- Gas Storage Tank: Run time=300 Sec & 4 - 5 Runs

Pressure : P1 = 2.066e+7 Pa (200 atm)

Volume : V1 = $68\ m^3 \times 4$

Laser Operation Requirements:

Flow Acoustics:

- Physical parameters :

$\gamma = 1.39$, $M = 31.25$g, $C_p = 730.4$ J/kg-K, & $c = 286.3$ m/s

$\beta = 4.063 \times 10^{-4}$ (Gladstone- Dale Coeff.)

- Medium homogeneity requirements :

$\Delta\rho/\rho$	BQ	
1.38×10^{-3}	2.0	
4.10×10^{-4}	1.1	
2.72×10^{-4}	1.05	@ $\lambda = 10\ \mu$ & $l = 3$ m

Acoustics Suppression

Pumping induced medium in homogeneity:

- $\Delta P/P = 0.94$ @ $P = 300$ J/l

Acoustic Suppression :

- **Flow direction**

  Expansion horn provides impedance match eliminating reflection of pressure waves

- **Normal to flow direction**

  Using acoustics muffler to dump out transverse pressure waves

  Muffler requirements:

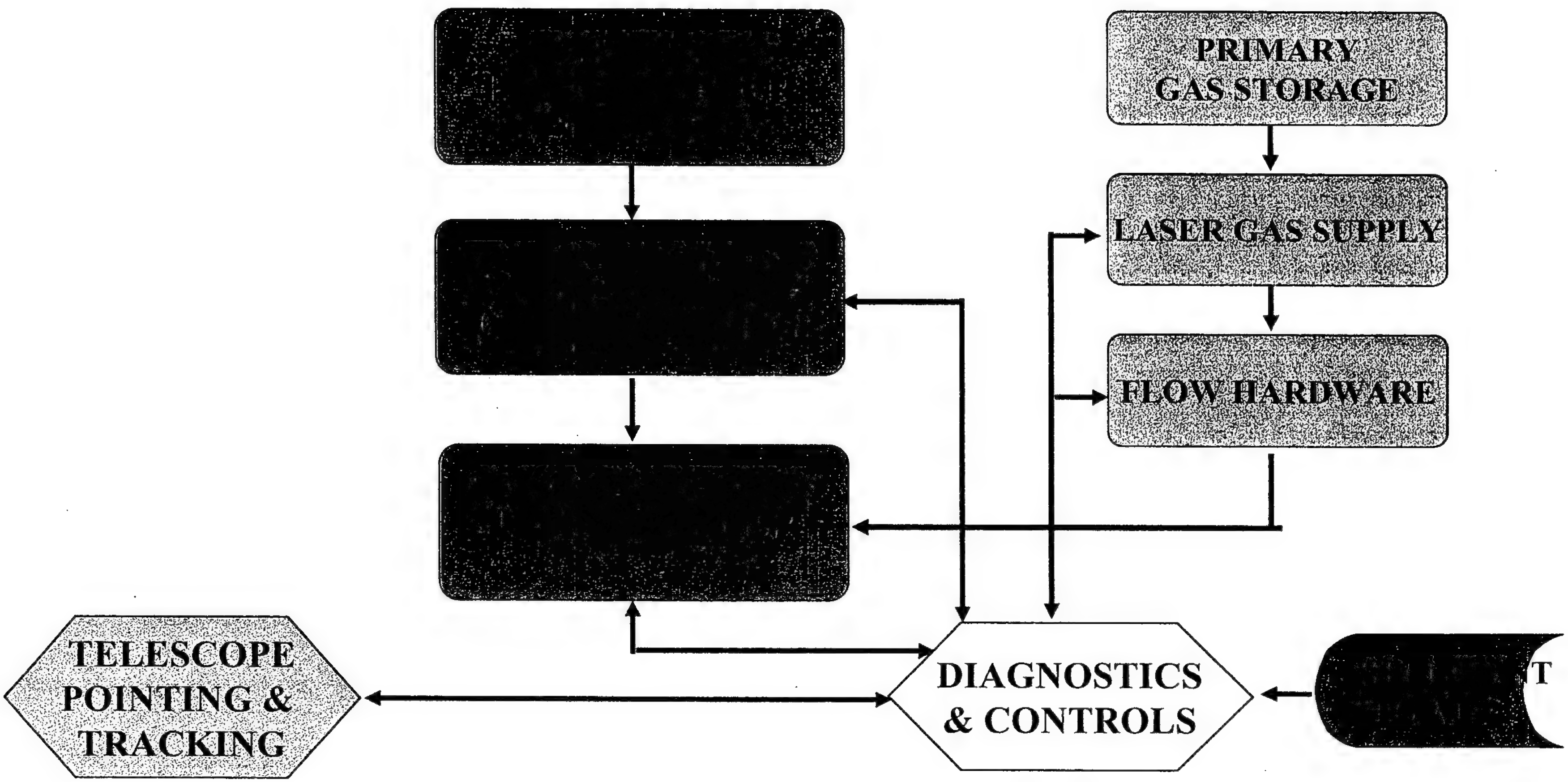
  Attenuation factor < 0.55

  Number of bounces between pulses : n =8 ($\Delta\rho/\rho \sim 1.0 \times 10^{-5}$)

Conceptual Design of Four-Unit Multi-Megawatt CO_2 Laser

- Beam Combining Concept
- Power Oscillator or Master Oscillator-Power Amplifier
  Unstable Resonator Cavity
  Grating & Rotating mirrors Beam-Combine Techniques
- Flow and Gas Handling System
  Blow down - Exhaust to Atmosphere
- Acoustics Suppression
  Expansion Horn Down Stream
  Anode Muffler

Transmitter Schematic Block Diagram For Single-Module Megawatt-Class Laser



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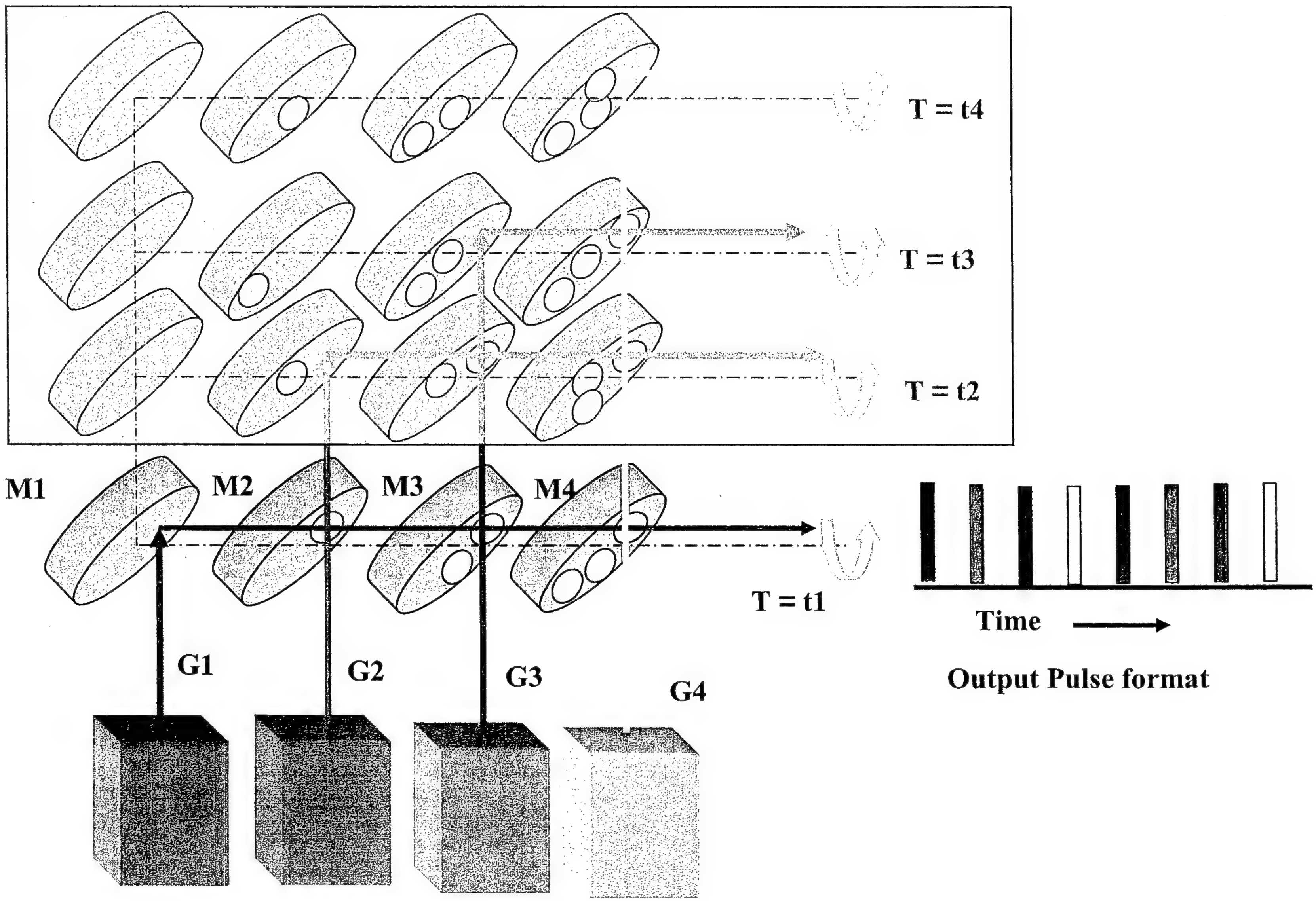
Beam Combining with Synchronized Rotating Mirrors



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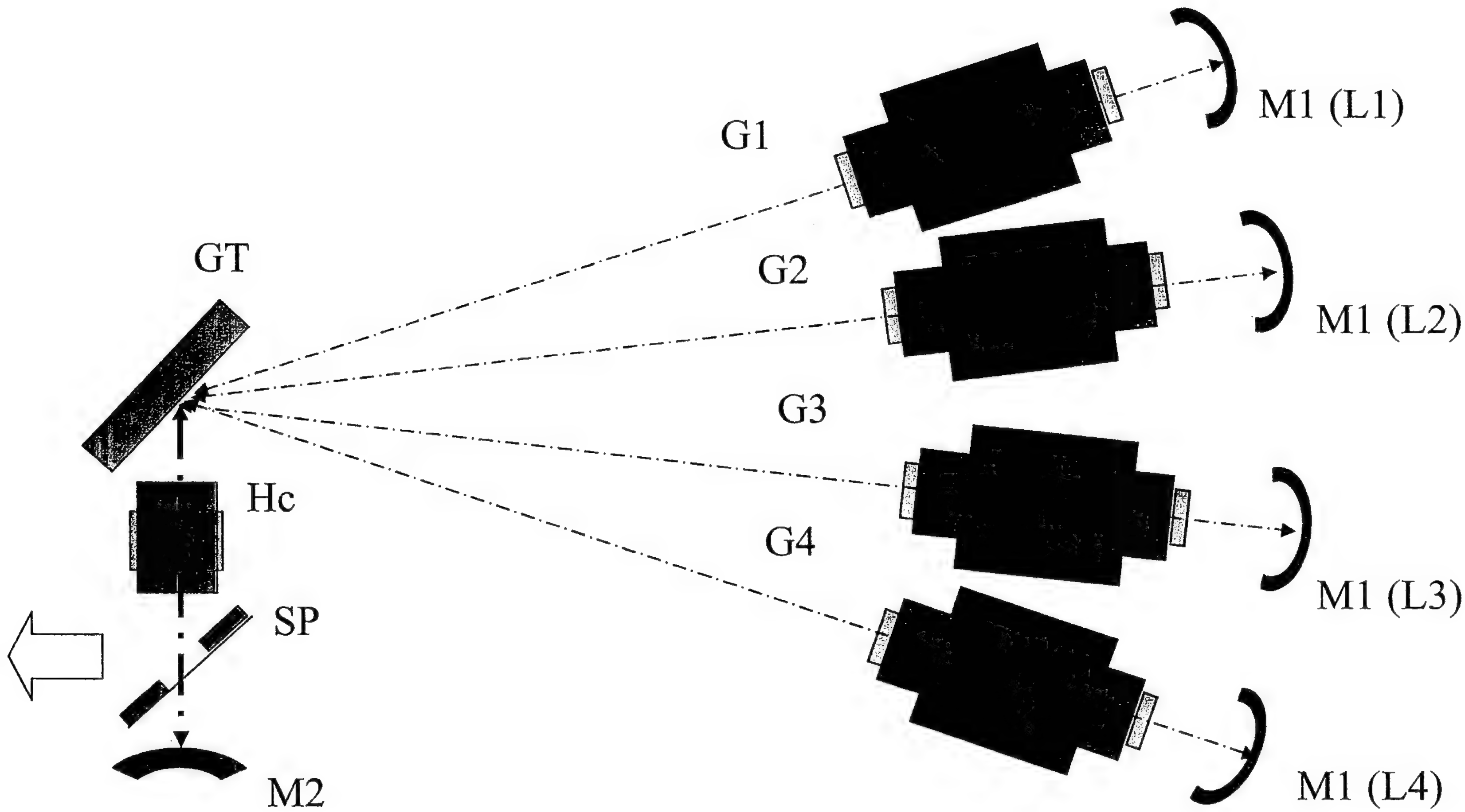
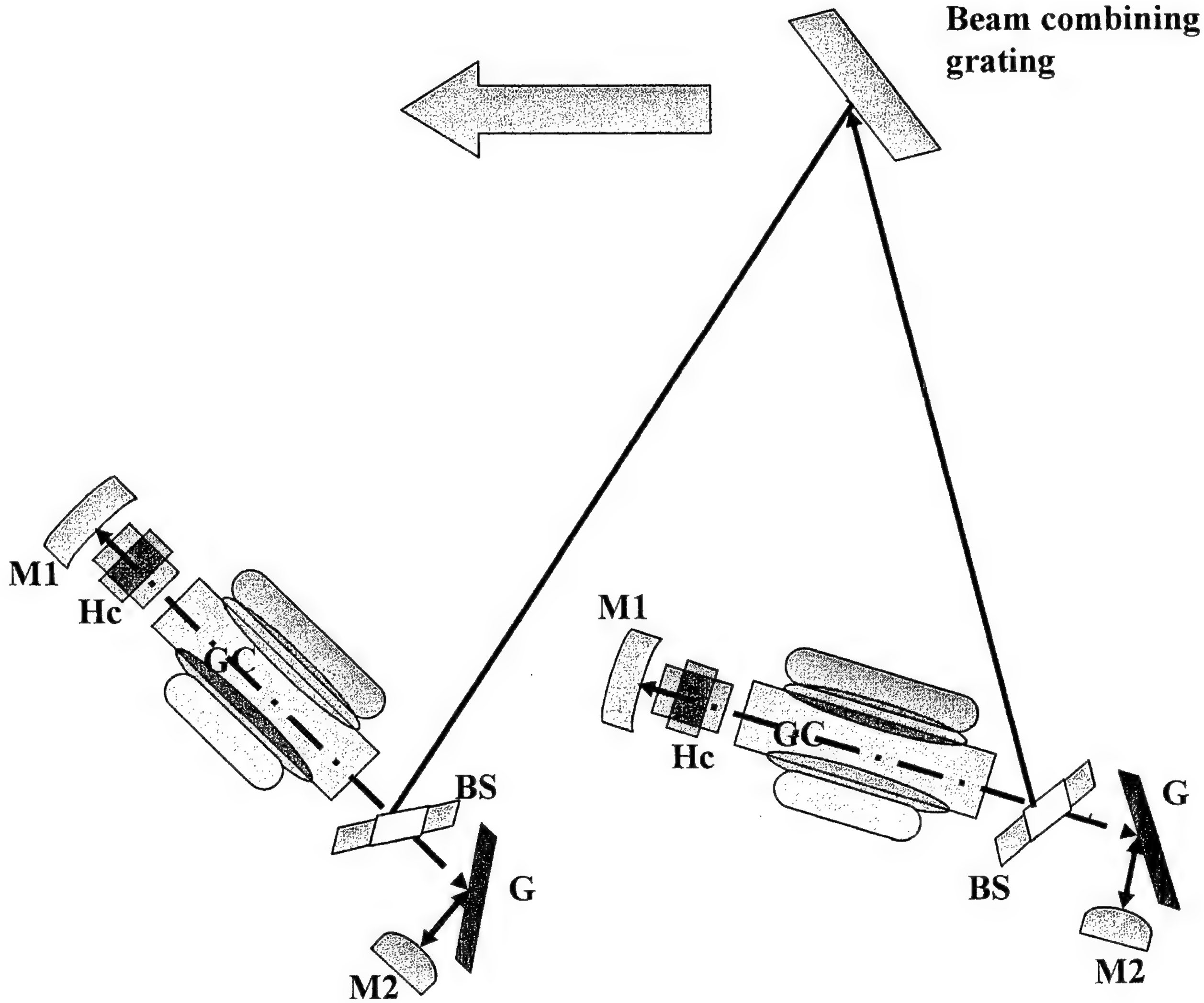
Conceptual Beam Combining with Hot Cell Intra-cavity



Conceptual External Beam Combining Design



M1 & M2 : Cavity mirrors
BS : Beam spliter
G : Intracavity Grating
Hc : Hot cell
GC : Laser Gain Medium

Oscillator Parameters for Each Transmitter

- Energy Loading: Ep = 300 J/l *
  Gain Vol = 0.27 m^3 (x4)
  A - K = 0.3 m
  Gain Length = 3 m
- Specific Laser Output = 65 J/l
- Estimated Extraction Efficiency: η=20%
- Rep Rate: R = 125 Hz @ 20μs
- Output Wavelengths ** : 10.6, 10.2, 9.6, & 9.3 μm (Mixed)
- Gas Mixture : 3:1:0.08 (N2:CO2:H2)
- Pressure : 1.013×10^5 Pa (1 Atm)
- Flash Factor : 1.3

** Select P & R Branch Lines in Both Bands

* Higher loadings at reduced gas temperature

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Optical Resonator Cavity : Optical Components

- Resonator Type: Confocal Unstable with Rotating Mirrors Beam Combining
  Magnification : M=4
  Cavity length : L=36.5m
  Equivalent Fresnel Number = 3.4
  Cavity Mirrors : M1 = 97.3m (concave) M2 =24.3m (convex)

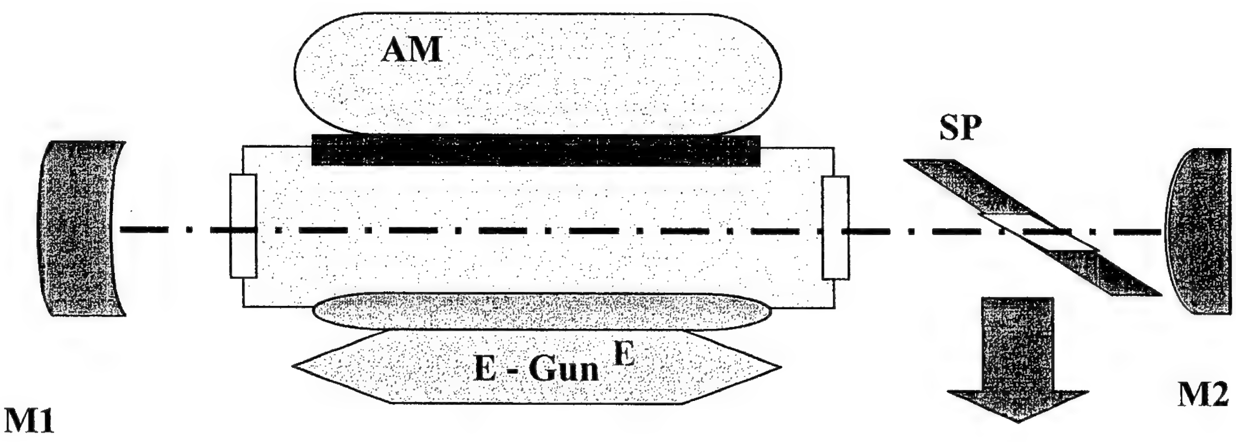
- Gain Cell : 0.3 x 0.3 x 3.0 m^3
  Gain Length : l = 3 m

- Beam Combine Mirrors : 75 x 75 cm^2 Flat (30x30 cm^2 apertures)
  @ $\lambda = 10.591\ \mu$ [I - P(20)]
  M1 (0 hole) M2 (1 hole)
  M3 (2 holes) M4 (3 holes)

- Low Pressure Hot Cell (Hc) : 0.3 - 0.5 Ghz suppression near line center

- Output Scraper Mirror : D = 0.075 m (tapered)

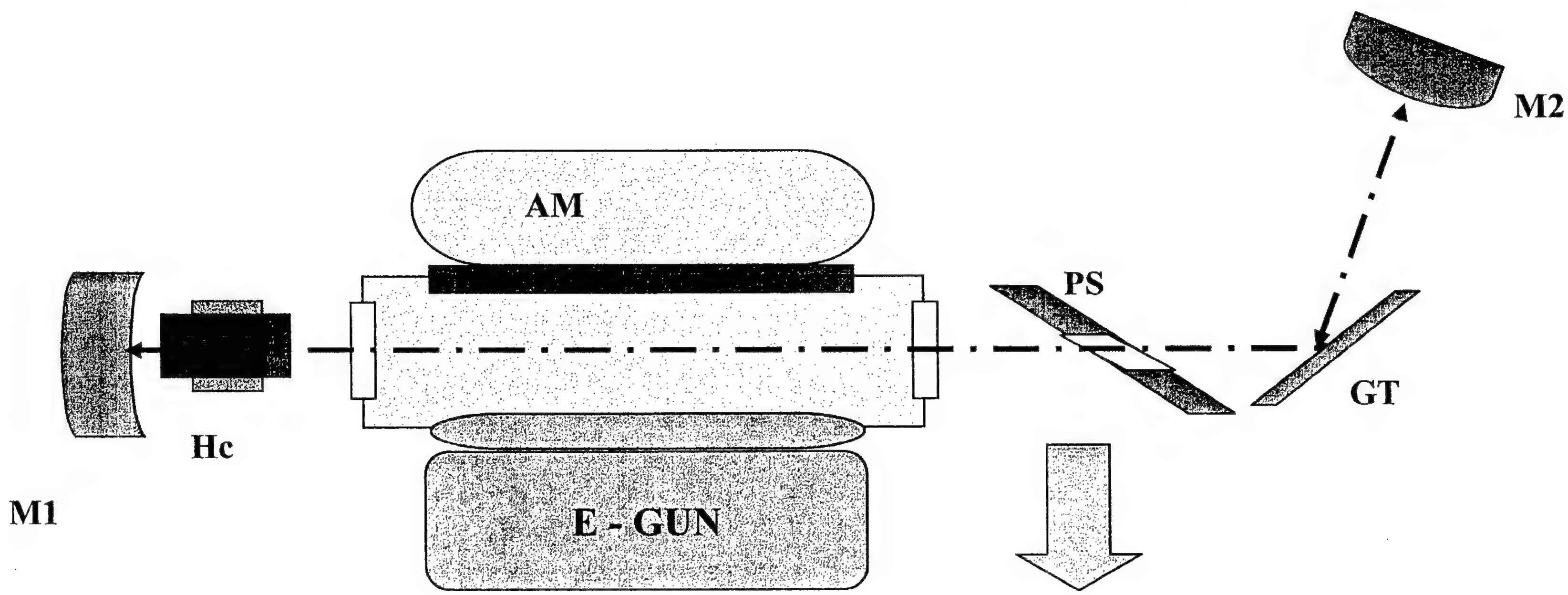
Power Oscillator : Optics



End Mirrors : M1 Concave (R1 =97m)
M2 Convex (R2=24m)
Magnification : M=4
Output Scraper: SP 36x36 cm (outer)
7.5x7.5 cm (inner)
Acoustic Muffler : AM
Electrodes : E

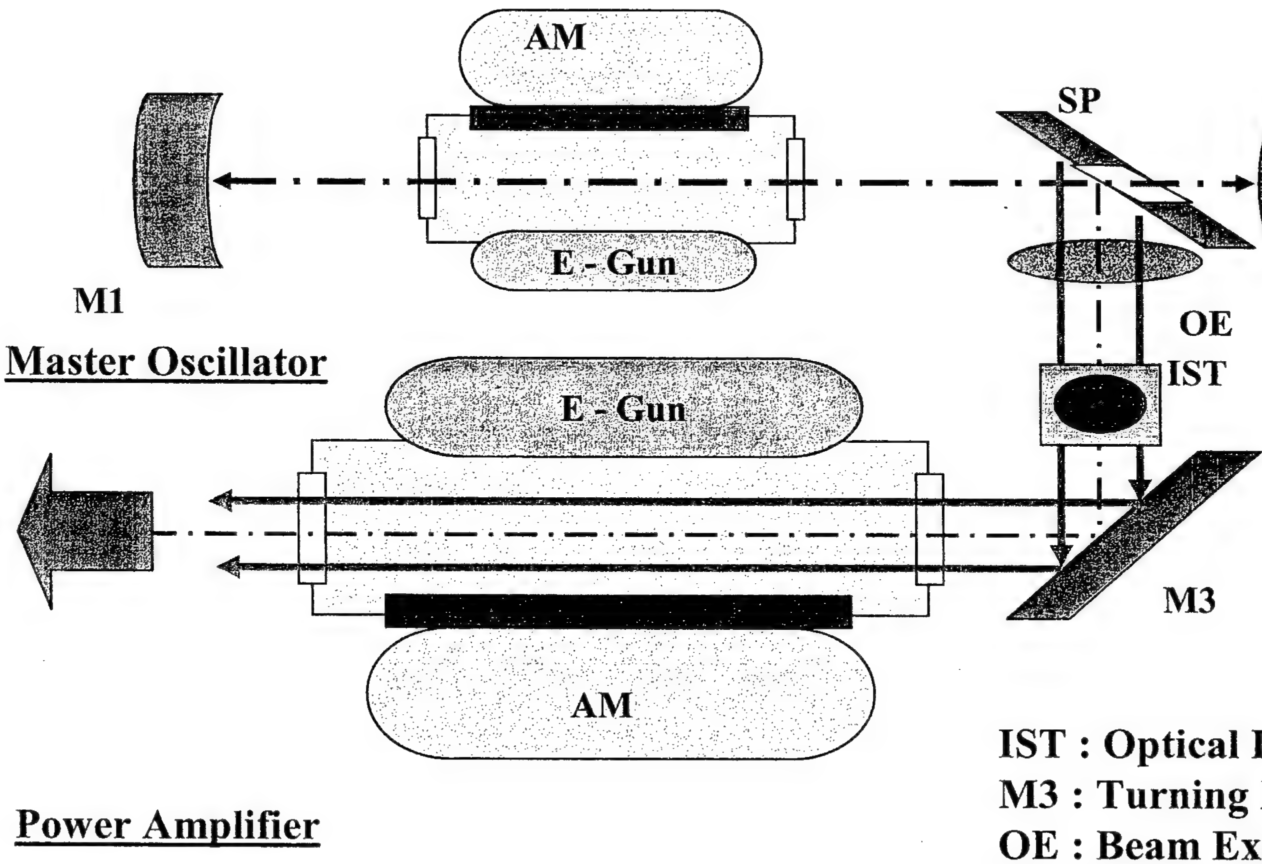
Cavity Length : 36.5m
Gain Length : 3m
Aperture : 0.3x0.3 m

Oscillator With Line Selection By Intracavity Hot Cell And Grating



M1 & M2 : End Mirrors
Hc : Hot Cell
AM : Acoustic Muffler
PS : Output Coupler
GT : Grating

Master Oscillator & Power Amplifier : MOPA



IST : Optical Isolator
M3 : Turning Flat
OE : Beam Expansion Optics
& Interface

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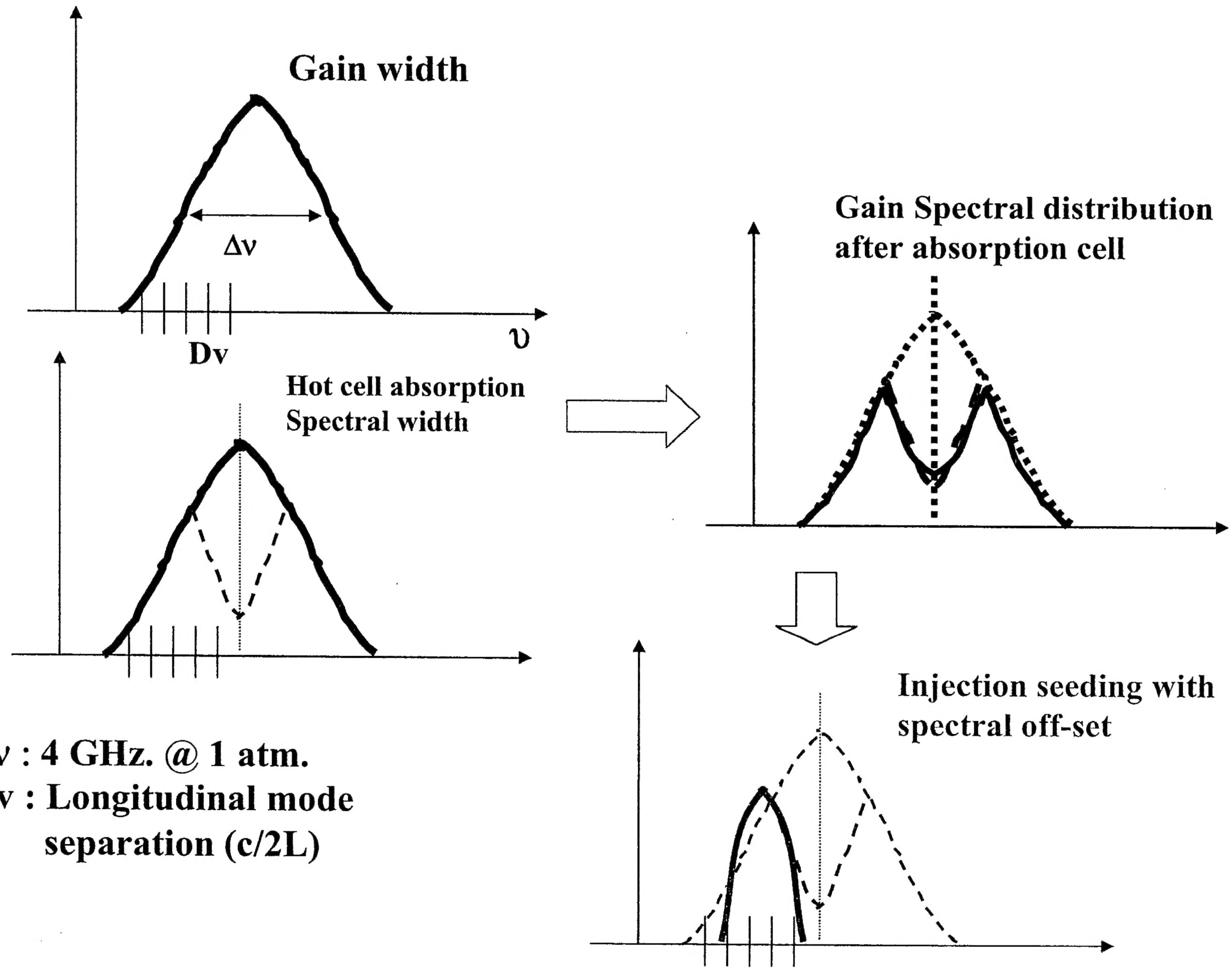
PROPOGATION ENHANCEMENT CONCEPTS

Peak Line Frequency Suppression Using Hot Absorption Cell



Δν : 4 GHz. @ 1 atm.
Dν : Longitudinal mode separation (c/2L)

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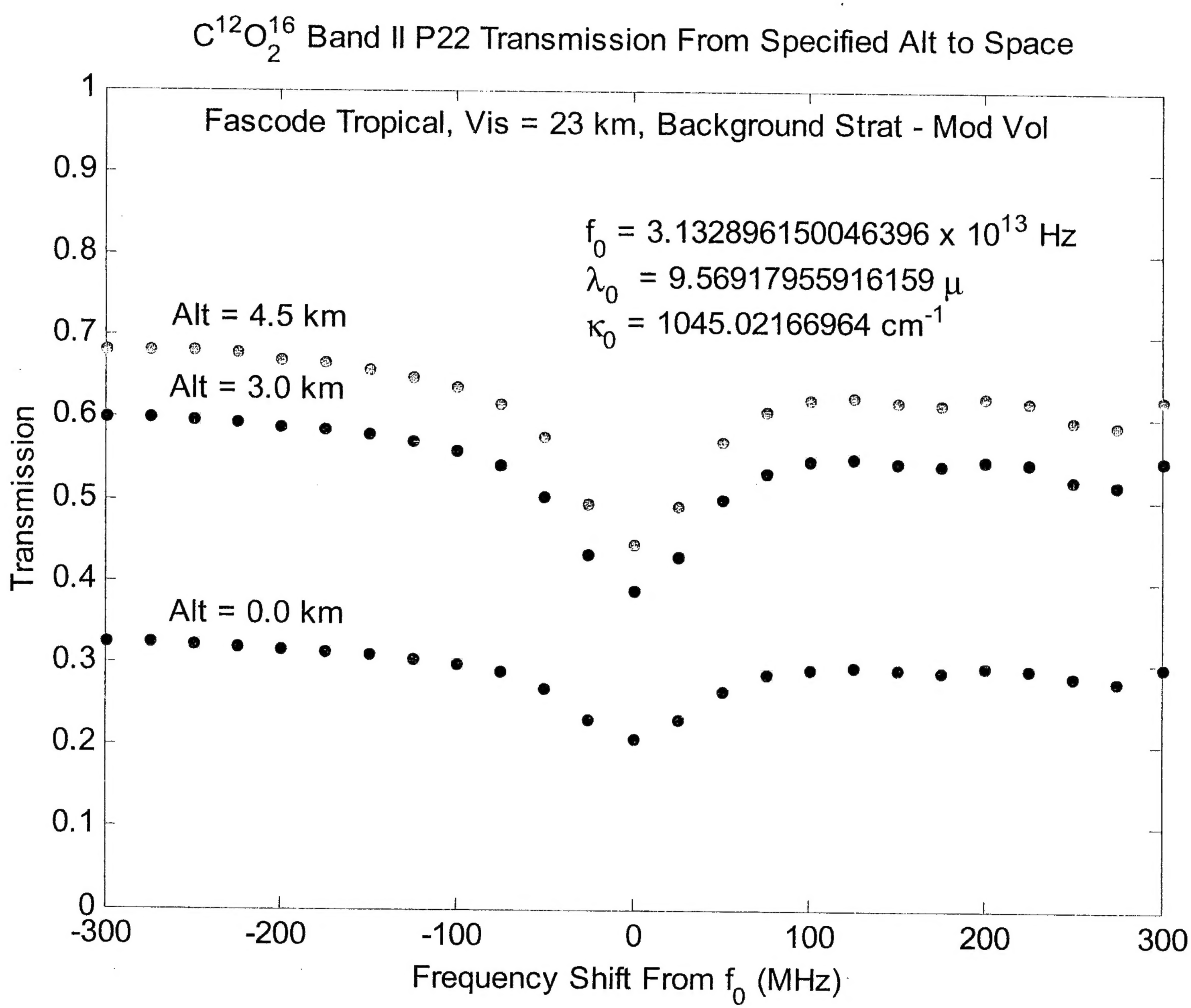

$C^{12}O_2^{16}$ Band II P22 Transmission From Specified Alt to Space
Fascode Tropical, Vis = 23 km, Background Strat - Mod Vol
f_0 = 3.132896150046396 x 10^{13} Hz
λ_0 = 9.56917955916159 μ
κ_0 = 1045.02166964 cm^{-1}
Alt = 4.5 km
Alt = 3.0 km
Alt = 0.0 km
Transmission
Frequency Shift From f_0 (MHz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-300
-200
-100
0
100
200
300

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CONCLUSIONS

- A PULSED CO_2 REPETITIVELY PULSED TRANSMITTER WIICH USES A 300-SECOND BLOWDOWN AND BEAM COMBINING CAN PROVIDE THE POWER LEVELS AND ENERGIES OF INTEREST
- SPECTRAL TAILORING AND MOUNTAIN TOP OPERATION SHOULD PROVIDE REASONABLE ATMOSPHERIC TRANSMISSION
- LOW COST OPERATION ACHIEVABLE WITH HELIUM-FREE GAS MIXTURES, WHICH USE NITROGEN, CARBON DIOXIDE AND SMALL QUANTITIES OF HYDROGEN
- SUBSCALE TEST WILL BE USED TO ANCHOR DESIGN AND THUS REDUCE RISK
- LEGACY PROGRAMS SUPPORT MANY ASPECTS OF THIS APPROACH
- GROWTH POTENTIAL WITH COLD-FLOW AND AERO WINDOWS SHOULD DOUBLE POWER OUTPUT